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Autonomous Mobility, Navigation, and Control for Venus Aerobots

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ABSTRACT

Balloons systems which operate under robotic control, called aerobots, offer rich potential for exploration of the planets. Telerobotics technology allows an aerobot to control its vertical motion and exploit prevailing winds to autonomously move to different planetary locations. In this paper we describe the position sensing, motion control, and path planning research efforts for a Venus-applicable aerobot.

1. BACKGROUND

Planetary exploration is evolving towards detailed in-situ exploration using mobile vehicles such as rovers and aerial vehicles. *Aerobots* are robotic aerovehicle systems which provide planetary scientists with a powerful new exploration capability [Cutts, Neck]. Current concepts for aerobots involve using balloons as the principal mobility mechanism since this requires **little on-board energy** for their operation as they are carried along by planetary winds. Figure 1 shows an artist's concept of what an aerobot might look like in the atmosphere of Venus.
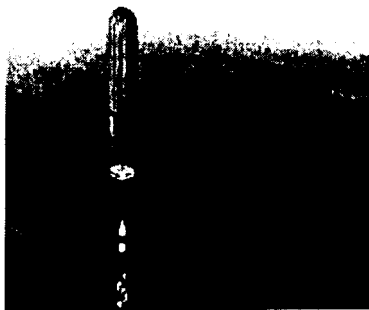

Figure 1: Aerobot at Venus

For planets such as the Earth and Venus-which have atmospheres that cool with increasing altitude—aerobots can be designed with control over vertical mobility by using a renewable non-ballasting buoyancy control technique [Jones]. Coupling this vertical mobility control into horizontal motion provided by planetary winds allows a sub-orbital planet-wide exploration capability. The vertical motion of an aerobot is driven by *phase change fluids* which are gaseous low in the atmosphere and condense readily at some point higher and cooler in the atmosphere. The aerobot's vertical motion, an oscillatory sinusoidal waveform about the condensation altitude of the fluid, with periods of several hours, is a natural by-product of the buoyancy change produced by the condensation and evaporation . Figure 2 shows an example ascent and oscillation. The condensation altitude for a typical phase change fluid at Venus is approximately 50km.
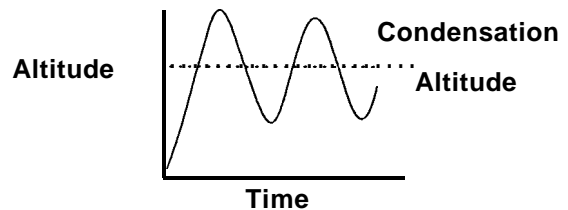

Figure 2. Aerobot Vertical Oscillations

The atmosphere and environment of Venus present unique and difficult challenges to scientific missions of any significant duration. The temperature at the surface of Venus is approximately 460° C at a pressure of 92 atmospheres. Constructing a probe which can survive such extreme temperature and pressure for a shod time is difficult, but has been done in previous Venus missions such as the Russian Venera landers. Higher in the atmosphere, the temperature is relatively cool. Aerobots offer the revolutionary capability to repeatedly explore the deep atmosphere of Venus as well as visit the surface of Venus for several hours at a time. At the end of each deep atmosphere excursion, the aerobot will rise high enough in the atmosphere to cool off. No previous technology (such as passive balloons, probes, or landers) can provide such capability for repeated ascents and descents.

Aerobots will help scientists answer many of the outstanding science questions about Venus such as

resolving questions of cloud chemistry, the structure of the deep atmosphere winds, driving mechanisms for the global circulation, and the nature of some anomalies in the Magellan radar data. In order for an aerobot to be maximally useful for science data collection, it must be able to do three things (1) determine where it is, (2) plan its motions, and (3) robustly execute its motions in an uncertain and changing 3D atmosphere. Aerobots are aerovehicles whose motions happen on a relatively fast time scale. Rovers can rest on the ground safely for hours *(or* days) while decisions are made on the Earth. Probes that fly for months or years in the predictable environment of space have ample time for Earth-based operators to construct operational sequences. An aerobot does not have that luxury; it must actively control its own motions even while it is out of radio contact with Earth. Telerobotics technology in the areas of aerobot position determination, path planning, and motion control provides the necessary on-board autonomy to allow viable aerobot operations. While other issues such as materials, thermal control, mechanical structure, power generation and science instrument design also represent key technical challenges, here we restrict ourselves to a discussion on telerobotics related issues.

2. TELEROBOTICS TECHNOLOGY

State/Location Determination: In order for science data collection to be most useful, it must be correlated with specific locations on the planet. Thus it is critical to know the location of the aerobot at all times. Unfortunately, the opaque upper cloud deck on Venus makes many conventional location determination technologies untenable, To determine its location, an aerobot on Venus will be forced to use a variety to techniques such as crude radio-frequency (RF) sensing of the sun, camera images of the surface, radar altimeter data, and beacon signals from orbiters or the Deep Space Network from Earth. In all cases, it will be critical to know the attitude of the aerobot's swinging instrument platform to do the required location calculations. The coupling of attitude estimation and global position determination is more complex and demanding than that for typical interplanetary spacecraft or rovers.

Vertical Mobility Modeling: Many desired science objectives for an aerobot science mission will require that the aerobot be able to control its vertical motion. The types of motions that will be possible include passive vertical oscillation, controlled descent, hovering, controlled ascent, and safe landing. Landings **will** require a landing snake (a slender flexible device hanging off the bottom of the aerobot) to

gently slow down the aerobot as it contacts the surface. Landing snakes may also host soil-sensing and collection hardware.

Path Planning: Scientists want to investigate specific features of Venus. For an aerobot to move to a desired location, it must use its vertical motion control to take advantage of the structure of the winds to move appropriately. This leads to a complex motion planning problem, There are several distinct types of motion planning that will be needed: short-term path prediction and monitoring to initiate obstacle avoidance, path planning to increase probability of the over-flight of a selected area, path planning to maximize over-flight of a set of selected targets (at specified altitudes), and path planning to fly as close to a specific target or land near it.

These technologies are applied to solve a number of aerobot mission goals.

2.1 Vertical Motion Control

Planetary winds provide the natural east-to-west motion for a Venus aerobot along a latitude. Vertical motion sensing, planning, and control is critical to achieving descent, hover, or landing near downwind targets along this wind-driven path. Vertical motion control is also a necessary precursor to utilizing the lateral winds at different altitudes to adjust the lateral ground track motion of the aerobot.

A key quantity that needs to be sensed is the downwind motion of the aerobot along the latitude band. As most of the nominal oscillatory motion of the aerobot will be in the clouds, this can be achieved through a combination of RF sun sensing to determine aerobot lognidtude and inertial dead-reckoning. Dead-reckoning drift can be minimized by azimuthal RF sun sensing. Special estimator models that encode the natural pendulum-style behavior of the aerobot allows the position to be optimally propagated with low errors.

The vertical motion control has unique features in that the control authority is one-sided-the rate of descent can only be slowed by releasing condensed phase change fluid into the evaporator. Furthermore, this control is only possible during that portion of the aerobot's vertical oscillation that is below the condensation altitude. A family of vertical motion primitives has been developed including ascent, oscillation, descent, and hover primitives. When concatenated in an appropriate manner, arbitrary feasible vertical motion profiles can be achieved

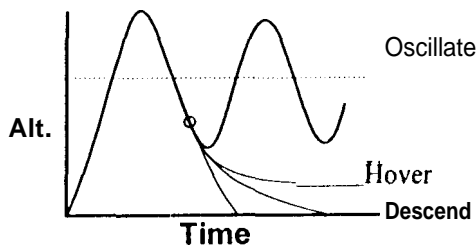subject to the constraints on the control. These are shown in Figure 3.

Figure 3: Trajectories

The thermodynamic models needed to support the simulation of the complex physics of reversible-fluid phase changes during vertical ascent and descent have already received extensive validation in the Earth's atmosphere using analogs to Venusian balloon materials and fluids. This is possible because of the similar temperature vs. altitude characteristics between the Earth's troposphere and the Venusian atmosphere.

Aerobot motions require significant amounts of time, and once initiated, often cannot be changed easily. As the control is unidirectional, and only valid during half of the natural oscillation cycle, committing to a control sequence requires careful planning. Planning consists of concatenating several vertical motion primitives and modifying the parametrization of the primitives to achieve desired motions. **Vertical** motion control of a simulated aerobot has been achieved. Representative models and planning algorithms for the Venusian atmosphere are also being developed.

Experiments required to support this development include testing of Inertial dead-reckoning and RF sun sensing techniques, calibration of the vertical motion primitives, and validation of the vertical motion plans and control actions on actual test flights using balloons with active valve control capabilities to regulate phase change fluid boiling..

2.2 lateral Motion **Control**

While an aerobot moves through the atmosphere of Venus its predominant ground-track is from east-to-west as it is carried by the zonal winds within a latitude band. As we have seen with vertical motion technology, the aerobot can be commanded to achieve various descents, hovers, landings and ascents along this down-wind trajectory. If the aerobot is required to achieve trajectories that are not simply described in terms of a down-wind motion, but are instead tied to actual ground-tracks described in planetary coordinates, then motion control must be exercised

both along zonal and meridonial directions, i.e. both east-west and north-south. North-south meridonial motions are possible utilizing atmospheric circulation winds - Hadley cells that transport air between the equator and the poles. These Hadley cells can be found at various altitudes in the atmosphere. They are expected to provide both north-to-south winds as well as south-to-north winds depending on the circulation patterns of the cell. However, the speed of these meridonial motions is expected to be less than the zonal winds, Thus 3D aerobot motion on Venus is not a generic point-to-point motion capability, but instead a control of a dominating east-to-west motion superimposed by a lateral north-to-south and south-to-north adjustments. Achieving this capability requires new technologies in sensing, wind modeling, and motion planning,

It is no longer sufficient to only sense the down-range motion, but lateral motions must also be determined. This is possible by using inertial propagation dead-reckoning techniques from an initial position obtained, for example, by a orbiter beacon Doppler measurement. However, in comparison with the extent of the motions involved, the relative accuracy in estimating lateral motion will be less than that for estimating the zonal motion. An independent and direct measurement of the actual ground-track motion is useful in reducing the size of estimation errors. The most promising technique is to use an image-based frame-to-frame **motion estimation methods to directly** determine the ground-track motion. Unfortunately this is only feasible during the day-time at very low altitudes because of the strong atmospheric scattering of sunlight back into the camera. However, this approach may be feasible as the aerobot dips below the clouds at night-time since the surface is then visible in the 1 micron band due to thermally emitted radiation from the surface. Highly efficient frame-to-frame registration algorithms have been developed and are being tested on ray-tracing simulations of the Venusian surface appearance. This will serve to confirm the feasibility of navigation imaging and establish error bounds on the motion estimates. A direct measurement of balloon ground-track velocity via Doppler analysis of a radar altimeter echo would also appear to be feasible,

Sensing is also required of the local wind-structure to assist in the planning of the motions. As the aerobot is carried in the winds, it is sufficient to estimate the velocity of the aerobot using the inertial and frame-to-frame imaging methods already discussed. Modeling and dealing with uncertain and changing global and local wind patterns is a serious technical problem that must be solved in order to fly the most effective aerobot science missions. Current models of the

circulation of the Venus atmosphere are very limited and uncertain. Therefore, an aerobot must be able to update its wind models on the fly. This is a difficult problem both in terms of how to adapt to new or changing conditions as well as how to do it efficiently enough to be done in an on-board computer. Wavelets are a promising technique which should allow explicit control of spatial resolution, controlled updating, and compact representations. Initial investigations undertaken in appear promising.

Motion planning to achieve the desired ground-tracks requires the integration of vertical and lateral motion planning. If the atmospheric circulation patterns are known, it is possible to use the vertical motion control to exploit the winds and move laterally. The amount of control over lateral motions depends on many factors including the extent of the vertical motion control and the knowledge and stability of wind patterns. This is a very interesting technical problem reminiscent of path planning for wheeled vehicles. Several types of maneuvers are anticipated-all designed to optimize the "dwell" time in a favorable lateral wind. The on-board controller will have to execute the plan with a significant amount of freedom to take advantages of favorable winds, when encountered. An adaptive circulation model will be a key technology for this function. In addition to more algorithmic methods, heuristic techniques derived from human trials of controlling simulated balloons may also be feasible. Data from manned earth flights undertaken as part of various balloon global circumnavigation expeditions could also be analyzed to bound motion planning performance.

Experiments to support these developments include image-based motion sensing using frame-to-frame image registration of synthetic Venus and stratospheric earth images, Doppler radar ground-track velocity measurements, confirmation of adaptive wind modeling using weather balloon launches, and test flights to validate the lateral motion planning techniques.

23 Global Target Optimization

The primary goal of an aerobot mission to Venus will be to address numerous scientific questions about the nature of the surface and geology of Venus. A variety of science targets will be selected beforehand and the aerobot will attempt to overfly or land as near to as many targets as possible. Given the uncertain knowledge of the Venusian atmospheric circulation **and the unique nature of the** aerobot **vertical control, it will probably** not be possible to fly directly to a specific target in general. On the contrary, the aerobot must be able to recognize and respond to targets of opportunity as is shown in Figure 4. This implies constant flight path prediction and mission target reachability analysis. When an opportunity arises, the aerobot must decide what to do, plan the appropriate descent trajectory, and execute it robustly.

Two key technologies are involved: global position estimation in planetary coordinates and motion planning and reachability analysis on a spherical planetary body. Whereas dead-reckoning propagation and sensing of local motion sufficed for short time-scale down-wind and lateral trajectory control, global position determination requires the addition of map-based sensing, sun sensing of terminator crossings and sun elevation angles, and orbiter assisted beacon-based radio-metric sensing,

Map-based methods can be image-based whereby a map of the Venusian surface is correlated to a global map, or it can be profile-based where a cross-sectional profile of the surface as revealed by the on-board altimeter is matched to the surface topography. On Venus, night-time surface images in the 1 micron band directly provide a measure of the topography because of high lapse rate in the atmosphere which causes higher surfaces to appear cooler (i.e. darker) in the image when compared to lower hotter (i.e. brighter) surfaces. As Magellan data provides high-resolution topography data, correlation is straightforward in principle. Practical implementation considerations as well as intrinsic variation in emmissivity require that direct correlation not be attempted and instead simpler correlations in "feature space" be used instead. Similar techniques can also be used with the altimeter profile data. Sun-sensing also provides a method for planet-wide localization as sun angle measurements serve to constrain the location of the aerobot. A similar approach is to monitor the angular location of a beacon signal transmitted from the Earth to the aerobot. Radio-metric measurements (1-way Doppler) of a relay orbiter's beacon signal also provides similar periodic constraints.

Given adequate position determination, desired science target locations, and reasonable vertical motion control, it will be useful to plan paths that maximize overflights or landings near desired targets, avoid obvious terrain hazards, and conform to the limited deep atmosphere dwell time imposed by the hot atmosphere of Venus. This planning requires optimization of the science return for a limited look-

ahead window (up to one or two aerobot circumnavigations of the planet). Using well-known search techniques, a plan for the limited look-ahead window will be constructed and set in motion. Executing the path will not be simple, since nothing will happen exactly as planned. Every descent into the lower atmosphere to shift latitude will not achieve precisely the desired latitude **shift.** Sometimes path error growth will simply mean small changes in the dwell time for the next descent; wheras at other imes it will completely alter what is best to do from that point on. So the plan will have to be repeatedly constructed and modified on-the-fly.   Having a clear measure of science return value is key to undertaking this optimization.

2.4 Aerobot Hazard Avoidance& Survival

Balloon hazard detection requires that imminent collision of the balloon with high terrain be detected sufficiently in advance to take evasive action. For a Venus aerobot, encountering hazardous terrain is a definite possibility when the system descends down to the surface for landing. The challenge is to distinguish the nominal, non-hazardous landing terrain below the aerobot from hazardous terrain relief in the horizontal path of the aerobot as it descends towards the landing point. The first class of terrain is benign and easily handled by the landing snake of the aerobot system whereas the second class of terrain could cause serious damage to the balloon envelope and systems.

It is proposed to use a radar altimeter ranging sensor to perform the terrain detection. This sensor utilizes radar signals and on-board signal processing to classify the return echoes from the terrain into a series of range intervals. Pattern recognition of the range intervals as they evolve with time allows the aerobot to distinguish between benign "flat" terrain that is suitable for landing from hazardous "craggy" terrain that constitutes a flight hazard. The seventy of the hazard is also a function of the horizontal velocity of the aerobot since otherwise mild hazards could become more dangerous with increased horizontal velocity of the aerobot system.

To avoid endangering the mission, the aerobot must be prepared to ascend rapidly when impending impact is suspected.   In addition to the radar altimeter sounding mentioned previously, the aerobot must constantly predict its trajectory as if it had just dumped all its condensed phase-change fluid into the evaporator and started to ascend as rapidly as possible. If the actual surface ahead of it approaches

this predicted profile, the aerobot should take immediate action to ascend,

Another necessity for aerobot survival is estimating maximum deepatmosphere dwell times given the thermodynamic limitations of the aerobot.   critical electronics and hardware of the aerobot will be contained   in   a   highly   insulated   gondola. Unfortunately, on-board heat generation and extremely high temperatures near the surface of Venus will not allow more than an hour or two of dwell time at low altitudes, At that point it will be necessary to ascend to the upper clouds to cool off.   In the previous discussion, the necessity for continual flight path projection was described. In a similar way, projections with a simplified thermal model will be necessary to determine if the planned flight profile will the thermally satisfactory.   There is a body of research on "homeostatic" self-monitoring and control which can be applied to the general question of how an aerobot can monitor its own conditions and plan its actions in order to fulfill its mission goals as well as protect itself[Arkin].

Experiments to be conducted include hazard detection tests with measurements of False Alarm and Miss probabilities, extrapolation of the results to different terrains, and validation of emergency ascent methods.

3. FUTURE WORK

The telerobotics research effort at JPL has concentrated on an end-to-end simulation of many of the telerobotics technologies necessary for a Venus aerobot mission, as well as experimental test of individual technology elements. The experiments range from simple stand-alone component experiments to fully integrated system demonstrations. Simulations using high fidelity models of the Venusian atmosphere, aerobot motion and planetary wind structure are being used to verify key telerobotics technologies. Small-scale experiments in the laboratory, earth-based small tropospheric balloons, and stratospheric test platforms are also being designed. In addition the Planetary Aerobot Testbed [Neck] is a small aerobot Earth-based balloon flight demonstration system that is being developed at JPL as part of the larger Aerobot Program.

PAT provides the necessary infrastructure, in terms of power, communication, gondola, cut-down systems,

aviation transponders, embedded computers, launch facility, and command and control stations, that is necessary to fly various buoyancy control, sensing, planning and science instrument experiments. To supped-the Venus aerobot effort, PAT will be configured with a phase change fluid buoyancy control system, Venus-applicable sensors, and Venus-specific vertical and lateral motion planning primitives developed in this telerobotic research effort.

Acknowledgments

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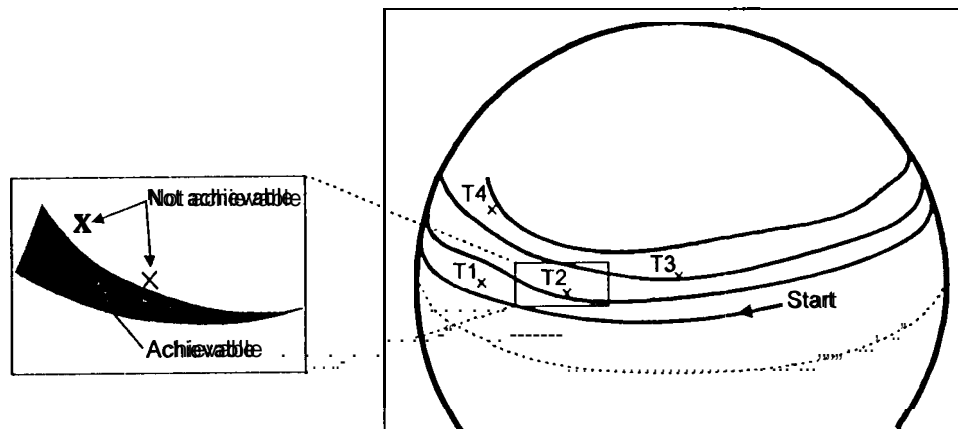
Figure 4: Possible Aerobot Path at Venus